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14. ABSTRACT
Emerging Navy research needs in structural acoustics and vibrations were met by a multifaceted research approach that engaged a Boston University research team in targeted and highly relevant investigations. In one facet, Professor J. Gregory McDaniel worked closely with Applied Physical Sciences to identify and pursue high-payoff research initiatives. His active participation in working meetings with this collaborator and others, as well as his focused time commitment to the project, allowed him to produce research findings and discoveries that benefit the largest collection of Navy-related activities. In another facet, Professor Pierre Dupont performed advanced development of mechanical realization theory. This theory answered the Navy's need for rapid and cost-effective testing by the guiding the construction of emulators, which are electro-mechanical models that approximate the input-output energy flow between machinery and the foundation on which it is mounted.

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Emerging Research Initiatives in Structural Acoustics and Vibrations

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Abstract

Emerging Navy research needs in structural acoustics and vibrations were met by a multifaceted research approach that engaged a Boston University research team in targeted and highly relevant investigations. In one facet, Professor J. Gregory McDaniel worked closely with Applied Physical Sciences to identify and pursue high-payoff research initiatives. His active participation in working meetings with this collaborator and others, as well as his focused time commitment to the project, allowed him to produce research findings and discoveries that benefit the largest collection of Navy-related activities. In another facet, Professor Pierre Dupont performed advanced development of mechanical realization theory. This theory answered the Navy's need for rapid and cost-effective testing by the guiding the construction of emulators, which are electro-mechanical models that approximate the input-output energy flow between machinery and the foundation on which it is mounted.

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Chapter 1

Collaborative Pursuit of Emerging Research Initiatives in Structural Acoustics and Vibrations

Professor McDaniel's sabbatical leave from Boston University was used to define university research directions that are benefitting the Navy by their strong relevance and focus. To achieve this, most activities involved close collaboration with Applied Physical Sciences, a consulting company involved in many Navy projects that interface with university research. Professor McDaniel also continued collaborations with Navy laboratories and a shipbuilding industries. These collaborations provided fresh perspectives on the relationships between university research and the Navy's unfolding needs. They also provided access to experimental data and computer models that were not available in a university setting. Progress in defining and pursuing research initiatives was accelerated by Professor McDaniel's attendance and contribution to frequent working meetings with collaborators in a variety of contexts and locations. The sabbatical leave also provided time to distill these meetings into forward-looking research plans. The remainder of the time was spent conducting research on selected topics chosen in consultation with ONR, as described in a later chapter. Key products of the research were progress reports detailing existing and future needs, surveying the scientific literature, and proposing future research. Findings were disseminated via lectures at society meetings, archival publications, and a lecture at the annual ONR program review.

1.1 Achievements

1.1.1 High-Payoff Research Initiatives

Throughout the performance period, Professor McDaniel met regularly with staff from Applied Physical Sciences and frequently communicated with researchers at shipbuilding industries, universities, and Naval laboratories. The two topics below emerged.

Wave propagation in anisotropic cylinders

After organizing and assessing literature on anisotropic composite cylinders, Professor McDaniel worked with Applied Physical Sciences to outline modeling needs. He also had initial discussions with Professor Morris at Notre Dame to explore testing of composite ducts in applications involving flows. In consultation with ONR, this topic was chosen for focused research. The results are detailed in Section 1.1.2 below.

Separation of overlapping signals

Structural acoustic testing often involves the measurement of signals that overlap in time. A classic example is the scattering of acoustic waves in complex environments, which creates distinct scattered waves arriving at distant hydrophones at different times. They often overlap in time, and one is interested in separating the signals to assess scattering from different objects or regions. Another example involves radiation from complex structures due to spatially and temporally localized excitations. In this case, sound is radiated from various portions of the structure and the radiated waves reached distant hydrophones at different types.

Professor McDaniel surveyed the literature on this subject and developed a formulation for separating signals. The formulation is based on an iterative approach that fits series of decaying sinusoids, each series with its own start time, to minimize the error between the data and the series. While the formulation is complete, it is hoped that an algorithm may be developed, tested, and deployed in the future.

1.1.2 Focused and Rapid Research

Dispersion predictions for anisotropic composite cylinders

Recent advances in composite materials offer the potential to dramatically affect the dispersions of helical waves that propagate in layered cylindrical shells. Effective choices and configurations of these materials require rapid dispersion predictions that take into account general anisotropy and variations of elastic variables through the thickness of each layer. Our work produced a solution to this problem that is based on a previously developed theory [J.G. McDaniel and J.H. Ginsberg, J. Appl. Mech. **60**, 463–469 (1993)] for the vibrations of cylindrical shells with isotropic layers. The approach uses propagating wave representations in the axial and circumferential coordinates. A series expansion with polynomial basis functions represents dependences on the radial coordinate and equations for the series coefficients are derived using the Rayleigh-Ritz Method. These equations yield a dispersion relation that is solved for the complex-valued axial wavenumber at each frequency and circumferential harmonic. Examples illustrate the interface of this approach with optimization algorithms that identify layer designs possessing specified dispersion properties.

Products of this effort are contained in the following documents:

- *Wave Propagation in Anisotropic Cylindrical Layers by Ritz Expansions*, Elizabeth

Ann Magliula, M.S. Thesis, Department of Aerospace and Mechanical Engineering, Boston University, 2005.

- "Analysis of wave dispersion in cylindrical shells with anisotropic layers by Rayleigh-Ritz expansions," Elizabeth Magliula, J. Gregory McDaniel, and Charles N. Corrado, October 2004, Volume 116, Issue 4, page 2521, presented at the *148th Meeting of the Acoustical Society of America*, San Diego, CA.

This work also resulted in a research proposal to ONR, entitled *Steering and Mixing Waves in Structures with Anisotropic Layers*, which was funded.

This work has received a great deal of interest from the Naval research community as well as the aerospace research community. In particular, Electric Boat was briefed on several occasions and is expected to be a recipient of findings and computer codes in future work. The research assistant who contributed to this achievement, Elizabeth Magliula, graduated from Boston University in May 2005 and is currently working at the Naval Undersea Weapons Center in related technical areas.

Effects of wave steering and mixing on acoustic radiation

In addition to developing formulations that predict dispersions of waves in layered analytical, Professor McDaniel also began to assess the affects of wave steering and mixing on acoustic radiation. *Wave steering* refers to the change in propagation direction of a wave, in our case caused primarily by the anisotropy of the structure. For infinite structures, one finds that wave steering has a negligible effect on radiation. However, this work showed that radiation from a finite cylindrical shell is influenced by the direction of propagation of structural waves. This effect will be more closely studied in the future.

Wave mixing refers to relative changes in the amplitudes of structural waves that are excited on a structure. For example, anisotropy may create a strong dependence of wave amplitudes on the orientation of a mechanical force. This effect was only briefly studied in this effort; it will be studied in detail in the future.

Chapter 2

Canonical Forms for Machinery Emulation

The goals of this task were to derive canonical forms for machinery emulators and to develop algorithms and procedures for implementing these forms as emulators. Emulators are electro-mechanical models that approximate the input-output energy flow between machinery and the foundation on which it is mounted. Such models are used in the scaled testing of novel ship structures. Examples of machinery for which the techniques could be applied include turbine generators, heat exchangers and pumps. The input-output energy flow can be characterized by forces and accelerations measured in one or more coordinate directions at the locations where the machinery attaches to its foundation. The design of emulators involves obtaining a mathematical model for the experimentally measured input-output behavior and converting that model to a form that can be interpreted as a simple electro-mechanical system. A canonical form in this context is the model which is simplest to build, which corresponds to the electromechanical system with the fewest components. Exact and approximate canonical forms were derived. Efficient numerical procedures for estimating their parameters were developed and all methods were tested experimentally.

2.1 Motivation and Potential Applications

Energy flow in and out of equipment is an important problem in naval design. Reducing the flow of vibrational energy from equipment to its supporting structures decreases noise propagation to the environment. Reduced acoustic signature can be important to avoiding detection by mines as well as by hostile vessels. Furthermore, the reduction of shock-event energy flow into equipment improves its survivability.

One of the major ways for controlling energy flow is through the development of novel ship structures that support the decks on which the machinery is mounted. Full-scale testing of design concepts is infeasible due to their large size and cost. Thus, quarter scale mechanical models are often employed. Deck-mounted machinery represents a substantial portion of the total system mass and thus its influence on overall energy flow in the system is also substantial. Furthermore, it is the machinery that generates much of the vibrational energy in a ship. Thus, the overall accuracy of the scale model testing were be closely tied to the accuracy of the machinery models in emulating both energy absorption and energy production.

At present, there are no established design procedures for equipment or machinery emulation. To date, the emulators used by the Navy have been limited to passive designs which have matched at most several modes and have considered a single attachment point. The goals of the proposed research were to develop emulator design tools which can be adapted to actual naval testing. To do so, tools with the following capabilities were derived: 1. Supports multiple attachment points (up to 4), 2. Applicable to a typical machine with up to 12 modes, 3. Can emulate both power-off and power-on states of machinery, 4. Provides emulation error measures, and 5. Provides supporting experimental procedures.

While the proposed theory and experimental procedures were developed in the context of machinery emulation, the products of this research can provide insight to several other Navy problems. The first of these is the shop-to-ship qualification of machinery. This problem involves predicting shipboard vibration levels from test data provided by the manufacturer. Such a comparison can be used to qualify replacement equipment as well as to predict overall noise signatures. A second potential application area arises from the trend to design ships that can accommodate modular payloads, i.e., payloads that can be swapped in and out based on mission requirements. In both application areas, the techniques to be developed could be adapted to assessing the salient machinery or payload dynamics as well as to suggest approaches for structural modifications to obtain desired input-output dynamics.

2.2 Achievements

2.2.1 Electromechanical Emulation of Active Vibratory Systems

Achievements in this area were described in the following paper: "Electromechanical Emulation of Active Vibratory Systems," W. Chen and P. Dupont, *JASA Express Letters*, accepted for publication October 2005. The design of a simple electromechanical system which is dynamically equivalent to an active vibratory system was studied in this paper. A two-step process is presented in which a passive vibratory system is first obtained, which is then modified in the second step to achieve active equivalence. Implementation of the active emulation step is achieved by closed-loop control of electromechanical shakers attached to the passive system and driven so as to generate the appropriate vibrations at the mounting locations of the active vibratory system. Experimental examples are used to demonstrate the effectiveness of this design process.

2.2.2 Realization of Mechanical Systems from Second-order Models

Achievements in this area were described in the following paper: "Realization of Mechanical Systems from Second-order Models," W. Chen and P. Dupont, *Journal of the Acoustical Society of America*, Vol. 118, No. 2, August 2005, pp. 762-773. Congruent coordinate transformations are used to convert second-order models to a form in which the mass, damping and stiffness matrices can be interpreted as a passive mechanical system. For those systems which can be constructed from interconnected mass, stiffness and damping elements, it is shown that the input-output preserving transformations can be parameterized by an orthogonal matrix whose dimension corresponds to the number of internal masses – those masses at which an input is not applied nor an output measured. Only a subset of these transformations result in mechanically realizable models. For models with a small number of internal masses, complete discrete mapping of the transformation space is possible permitting enumeration of all mechanically realizable models sharing the original model's input-output behavior. When the number of internal masses is large, a nonlinear search of transformation space can be employed to identify mechanically realizable models. Applications include scale model vibration testing of complicated structures and the design of electro-mechanical filters.

Chapter 3

Publications, Presentations, and Honors

3.1 Publications

The project produced the following publications:

- "Electromechanical Emulation of Active Vibratory Systems," W. Chen and P. Dupont, *JASA Express Letters*, accepted for publication October 2005.
- "Realization of Mechanical Systems from Second-order Models," W. Chen and P. Dupont, *Journal of the Acoustical Society of America*, Vol. 118, No. 2, August 2005, pp. 762-773.
- *Mechanical Realization Theory and Its Application to Machinery Emulation*, Wenyuan Chen, Ph.D. Dissertation, Department of Aerospace and Mechanical Engineering, Boston University, 2004.
- *Wave Propagation in Anisotropic Cylindrical Layers by Ritz Expansions*, Elizabeth Ann Magliula, M.S. Thesis, Department of Aerospace and Mechanical Engineering, Boston University, 2005.

3.2 Presentations

The project produced the following presentations:

- "Analysis of wave dispersion in cylindrical shells with anisotropic layers by Rayleigh-Ritz expansions," Elizabeth Magliula, J. Gregory McDaniel, and Charles N. Corrado, October 2004, Volume 116, Issue 4, page 2521, presented at the *148th Meeting of the Acoustical Society of America*, San Diego, CA.

- "Mixing and Steering Waves in Anisotropic Structures: Benchmarks and Initial Findings," J. Gregory McDaniel, FY–2005 Joint Review of ONR Computational Mechanics and Structural Acoustics Programs, April 20, 2005.
- "Causality Conclusions and Dispersion Predictions," J. Gregory McDaniel, FY–2004 Joint Review of ONR Computational Mechanics and Structural Acoustics Programs, April 22, 2004.

3.3 Honors

Elizabeth Magliula won Second Place in the Best Student Paper in Structural Acoustics from the Acoustical Society of America, based on her presentation at the *148th Meeting of the Acoustical Society of America.*

Chapter 4

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